SUMMARY

Life in 2015 will be revolutionized by the growing effect of multidisciplinary technology across all dimensions of life: social, economic, political, and personal. Biotechnology will enable us to identify, understand, manipulate, improve, and control living organisms (including ourselves). The revolution of information availability and utility will continue to profoundly affect the world in all these dimensions. Smart materials, agile manufacturing, and nanotechnology will change the way we produce devices while expanding their capabilities. These technologies may also be joined by "wild cards" in 2015 if barriers to their development are resolved in time.

The results could be astonishing. Effects may include significant improvements in human quality of life and life span, high rates of industrial turnover, lifetime worker training, continued globalization, reshuffling of wealth, cultural amalgamation or invasion with potential for increased tension and conflict, shifts in power from nation states to non-governmental organizations and individuals, mixed environmental effects, improvements in quality of life with accompanying prosperity and reduced tension, and the possibility of human eugenics and cloning.

The actual realization of these possibilities will depend on a number of factors, including local acceptance of technological change, levels of technology and infrastructure investments, market drivers and limitations, and technology breakthroughs and advancements. Since these factors vary across the globe, the implementation and effects of technology will also vary, especially in developing countries. Nevertheless, the overall revolution and trends will continue through much of the developed world.

The fast pace of technological development and breakthroughs makes foresight difficult, but the technology revolution seems globally significant and quite likely.

Interacting trends in biotechnology, materials technology, and nanotechnology as well as their facilitations with information technology are discussed in this report. Additional research and coverage specific to information technology can be found in Hundley et al., 2000, and Anderson et al., 2000 [212, 213].[1]

[1] Bracketed numbers indicate the position of the reference in the bibliography.

THE REVOLUTION OF LIVING THINGS

Biotechnology will begin to revolutionize life itself by 2015. Disease, malnutrition, food production, pollution, life expectancy, quality of life, crime, and security will be significantly addressed, improved, or augmented. Some advances could be viewed as accelerations of human-engineered evolution of plants, animals, and in some ways even humans with accompanying changes in the ecosystem. Research is also under way to create new, free-living organisms.

The following appear to be the most significant effects and issues:

- **Increased quantity and quality of human life.** A marked acceleration is likely by 2015 in the expansion of human life spans along with significant improvements in the quality of human life. Better disease control, custom drugs, gene therapy, age mitigation and reversal, memory drugs, prosthetics, bionic implants, animal transplants, and many other advances may continue to increase human life span and improve the quality of life. Some of these advances may even improve human performance beyond current levels (e.g., through artificial sensors). We anticipate that the developed world will lead the developing world in reaping these benefits as it has in the past.
- **Eugenics and cloning.** By 2015 we may have the capability to use genetic engineering techniques to "improve" the human species and clone humans. These will be very controversial developments—among the most controversial in the entire history of mankind. It is unclear whether wide-scale efforts will be initiated by 2015, and cloning of humans may not be technically feasible by 2015. However, we will probably see at least some narrow attempts such as gene therapy for genetic diseases and cloning by rogue experimenters. The controversy will be in full swing by 2015 (if not sooner).

Thus, the revolution of biology will not come without issue and unforeseen redirections. Significant ethical, moral, religious, privacy, and environmental debates and protests are already being raised in such areas as genetically modified foods, cloning, and genomic profiling. These issues should not halt this revolution, but they will modify its course over the next 15 years as the population comes to grips with the new powers enabled by biotechnology.

The revolution of biology relies heavily on technological trends not only in the biological sciences and technology but also in microelectromechanical systems, materials, imaging, sensor, and information technology. The fast pace of technological development and breakthroughs makes foresight difficult, but advances in genomic profiling, cloning, genetic modification, biomedical engineering, disease therapy, and drug developments are accelerating.

ISSUES IN BIOTECHNOLOGY

Despite these potentials, we anticipate continuing controversy over such issues as:

- Eugenics;
- Cloning of humans, including concerns over morality, errors, induced medical problems, gene ownership, and human breeding;
- Gene patents and the potential for either excessive ownership rights of sequences or insufficient intellectual property protections to encourage investments;
- The safety and ethics of genetically modified organisms;
- The use of stem cells (whose current principal source is human embryos) for tissue engineering;
- Concerns over animal rights brought about by transplantation from animals as well as the risk of trans-species disease;
- Privacy of genetic profiles (e.g., nationwide police databases of DNA profiles, denial of employment or insurance based on genetic predispositions);
- The danger of environmental havoc from genetically modified organisms (perhaps balanced by increased knowledge and control of modification functions compared to more traditional manipulation mechanisms);
- An increased risk of engineered biological weapons (perhaps balanced by an increased ability to engineer countermeasures and protections).

Nevertheless, biomedical advances (combined with other health improvements) will continue to increase human life span in those countries where they are applied. Such advances are likely to lengthen individual productivity but also will accentuate such issues as shifts in population age, financial support for retired people, and increased health care costs for individuals.

THE REVOLUTION OF MATERIALS, DEVICES, AND MANUFACTURING

Materials technology will produce products, components, and systems that are smaller, smarter, multi-functional, environmentally compatible, more survivable, and customizable. These products will not only contribute to the growing revolutions of information and biology but will have additional effects on manufacturing, logistics, and personal lifestyles.

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Smart Materials

Several different materials with sensing and actuation capabilities will increasingly be used to combine these capabilities in response to environmental conditions. Applications that can be foreseen include:

- Clothes that respond to weather, interface with information systems, monitor vital signs, deliver medicines, and protect wounds;
- Personal identification and security systems; and
- Buildings and vehicles that automatically adjust to the weather.

Increases in materials performance for power sources, sensing, and actuation could also enable new and more sophisticated classes of robots and remotely guided vehicles, perhaps based on biological models.

Agile Manufacturing

Rapid prototyping, together with embedded sensors, has provided a means for accelerated and affordable design and development of complex components and systems. Together with flexible manufacturing methods and equipment, this could enable the transition to agile manufacturing systems that by 2015 will facilitate the development of global business enterprises with components more easily specified and manufactured across the globe.

Nanofabricated Semiconductors

Hardware advances for exponentially smaller, faster, and cheaper semiconductors that have fueled information technology will continue to 2015 as the transistor gate length shrinks to the deep, 20–35 nanometer scale. This trend will increase the availability of low-cost computing and enable the development of ubiquitous embedded sensors and computational systems in consumer products, appliances, and environments.

By 2015, nanomaterials such as semiconductor “quantum dots” could begin to revolutionize chemical labeling and enable rapid processing for drug discovery, blood assays, genotyping, and other biological applications.

Integrated Microsystems

Over the next 5–10 years, chemical, fluidic, optical, mechanical, and biological components will be integrated with computational logic in commercial chip designs. Instrumentation and measurement technologies are some of the most promising areas for near-term advancements and enabling effects. Biotechnology research and production, chemical synthesis, and sensors are all likely to be substantially improved by these advances by 2015. Even entire systems (such as satellites and automated laboratory processing equipment) with integrated microscale components will be built at a fraction of the cost of current macroscale systems, revolutionizing the sensing and processing of information in a variety of civilian and military applications. Advances might also enable the proliferation of some currently controlled processing capabilities (e.g., nuclear isotope separation).

TECHNOLOGY WILD CARDS

Although the technologies described above appear to have the most promise for significant global effects, such foresights are plagued with uncertainty. As time progresses, unforeseen technological developments or effects may well eclipse these trends. Other trends that because of technical challenges do not yet seem likely to have significant global effects by 2015 could become significant earlier if breakthroughs are made. Consideration of such “wild cards” helps to round out a vision of the future in which ranges of possible end states may occur.

Novel Nanoscale Computers

In the years following 2015, serious difficulties in traditional semiconductor manufacturing techniques will be reached. One potential long-term solution for overcoming obstacles to increased computational power is to shift the basis of computation to devices that take advantage of various *quantum* effects. Another approach known as *molecular electronics* would use chemically assembled logic switches organized in large numbers to form a computer. These concepts are attractive because of the huge number of parallel, low-power devices that could be developed, but they are not anticipated to have significant effects by 2015. Research will progress in these and other alternative computational paradigms in the next 15 years.

Molecular Manufacturing

A number of visionaries have advanced the concept of molecular manufacturing in which objects are assembled atom-by-atom (or molecule-by-molecule) from the bottom up (rather than from the top down using conventional fabrication techniques). Although molecular manufacturing holds the promise of significant global changes (e.g., major shifts in manufacturing technology with accompanying needs for worker retraining and opportunities for a new manufacturing paradigm in some product areas), only the most fundamental results for molecular manufacturing currently exist in isolation at the research stage. It is certainly reasonable to expect that a small-scale integrated capability could be developed over the next 15 years, but large-scale effects by 2015 are uncertain.

Self-Assembly

Though unlikely to happen on a wide scale by 2015, self-assembly methods (including the use of biological approaches) could ultimately provide a challenge to top-down semiconductor lithography and molecular manufacturing.

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META-TRENDS AND IMPLICATIONS

Taken together, the revolution of information, biology, materials, devices, and manufacturing will create wide-ranging trends, concerns, and tensions across the globe by 2015.

- **Accelerating pace of technological change.** The accelerating pace of technological change combined with "creative destruction"[2] of industries will increase the importance of continued education and training. Distance learning and other alternative mechanisms will help, but such change will make it difficult for societies reluctant to change. Cultural adaptation, economic necessity, social demands, and resource availabilities will affect the scope and pace of technological adoption in each industry and society over the next 15 years. The pace and scope of such change could in turn have profound effects on the economy, society, and politics of most countries. The degree to which science and technology can accomplish such change and achieve its benefits will very much continue to depend on the will of those who create, promote, and implement it.
- **Increasingly multidisciplinary nature of technology.** Many of these technology trends are enabled by multidisciplinary contributions and interactions. Biotechnology will rely heavily on laboratory equipment providing lab-on-a-chip analysis as well as progress in bioinformatics. Microelectromechanical systems (MEMS) and smart and novel materials will enable small, ubiquitous sensors. Also, engineers are increasingly turning to biologists to understand how living organisms solve problems in dealing with a natural environment; such "biomimetic" endeavors combine the best solutions from nature with artificially engineered components to develop systems that are better than existing organisms.
- **Competition for technology development leadership.** Leadership and participation in development in each technical area will depend on a number of factors, including future regional economic arrangements (e.g., the European Union), international intellectual property rights and protections, the character of future multi-national corporations, and the role and amount of public- and private-sector research and development (R&D) investments. Currently, there are moves toward competition among regional (as opposed to national) economic alliances, increased support for a global intellectual property protection regime, more globalization, and a division of responsibilities for R&D funding (e.g., public-sector research funding with private-sector development funding).
- **Continued globalization.** Information technology, combined with its influence on other technologies (e.g., agile manufacturing), should continue to drive globalization.

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[2]Creative destruction can be defined as "the continuous process by which emerging technologies push out the old" (Greenspan, 1999 [10]. The original use of the phrase came from Joseph A. Schumpeter's work *Capitalism, Socialism, and Democracy* (Harper & Brothers, New York, 1942, pp. 81–86).

- **Latent lateral penetration.** Older, established technologies will trickle into new markets and applications through 2015, often providing the means for the developing world to reap the benefits of technology (albeit after those countries that invest heavily in infrastructure and acquisition early on). Such penetration may involve innovation to make existing technology appropriate to new conditions and needs rather than the development of fundamentally new technology.

Concerns and Tensions

Concerns and tensions regarding the following issues already exist in many nations today and will grow over the next 15 years:

- **Class disparities.** As technology brings benefits and prosperity to its users, it may leave others behind and create new class disparities. Although technology will help alleviate some severe hardships (e.g., food shortages and nutritional problems in the developing world), it will create real economic disparities both between and within the developed and developing worlds. Those not willing or able to retrain and adapt to new business opportunities may fall further behind. Moreover, given the market weakness of poor populations in developing countries, economic incentives often will be insufficient to drive the acquisition of new technology artifacts or skills.
- **Reduced privacy.** Various threats to individual privacy include the construction of Internet-accessible databases, increased sensor capability, DNA testing, and genetic profiles that indicate disease predispositions. There is some ambivalence about privacy because of the potential benefits from these technologies (e.g., personalized products and services). Since legislation has often lagged behind the pace of technology, privacy may be addressed in reactive rather than proactive fashion with interleaving gaps in protection.
- **Cultural threats.** Many people feel that their culture's continued vitality and possibly even long-term existence may be threatened by new ways of living brought about by technology. As the benefits of technology are seen (especially by younger generations), it may be more difficult to prevent such changes even though some technologies can preserve certain cultural artifacts and values and cultural values can have an impact on guiding regulations and protections that affect technological development.

CONCLUSIONS

Beyond the agricultural and industrial revolutions of the past, a broad, multidisciplinary *technology revolution* is changing the world. Information technology is already revolutionizing our lives (especially in the developed world) and will continue to be aided by breakthroughs in materials and nanotechnology. Biotechnology will revolutionize living organisms. Materials and nanotechnology will enable the development of new devices with unforeseen capabilities. Not only are these technologies having impact on our lives, but they are heavily intertwined, making the technology revolution highly multidisciplinary and accelerating progress in each area.

The revolutionary effects of biotechnology may be the most startling. Collective breakthroughs should improve both the quality and length of human life. Engineering of the environment will be unprecedented in its degree of intervention and control. Other technology trend effects may be less obvious to the public but in hindsight may be quite revolutionary. Fundamental changes in what and how we manufacture will produce unprecedented customization and fundamentally new products and capabilities.

Despite the inherent uncertainty in looking at future trends, a range of technological possibilities and impacts are foreseeable and will depend on various enablers and barriers (see Table S.1).

These revolutionary effects are not proceeding without issue. Various ethical, economic, legal, environmental, safety, and other social concerns and decisions must be addressed as the world's population comes to grips with the potential effects these trends may have on their cultures and their lives. The most significant issues may be privacy, economic disparity, cultural threats (and reactions), and bioethics. In particular, issues such as eugenics, human cloning, and genetic modification invoke the strongest ethical and moral reactions. These issues are highly complex since they both drive technology directions and influence each other in secondary and higher-order ways. Citizens and decisionmakers need to inform themselves about technology, assembling and analyzing these complex interactions in order to truly understand the debates surrounding technology. Such steps will prevent naive decisions, maximize technology's benefit given personal values, and identify inflection points at which decisions can have the desired effect without being negated by an unanalyzed issue.

Technology's promise is here today and will march forward. It will have widespread effects across the globe. Yet, the technology revolution will not be uniform in its effect and will play out differently on the global stage depending on acceptance, investment, and a variety of other decisions. There will be no turning back, however, since some societies will avail themselves of the revolution, and globalization will thus change the environment in which each society lives. The world is in for significant change as these advances play out on the global stage.

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Table S.1

The Range of Some Potential Interacting Areas and Effects of the Technology Revolution by 2015

Smart materials $\xrightarrow{\text{Facilitates}}$ Integrated microsystems $\longrightarrow$ Information technology $\xrightarrow{\text{Facilitates}}$ Genetic manipulation

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	Smart materials	Integrated microsystems	Information technology	Genetic manipulation
High-growth futures	**Enabled pervasive systems** Continuous body function monitoring Targeted, noninvasive drug delivery Pervasive sensors and displays (wearable, structural) Weather-responsive shelters Shape-changing vehicle components Seamless virtual reality **Effects** Improved life span Improved life quality and health Increased energy efficiency and reduced environmental effects Continued growth of entertainment industries	**Wide, multi-modal integration** Laboratory analysis-on-a-chip Pervasive sensors (biological, chemical, optical, etc.) Micro- and nanosatellites Micro-robots **Effects** Facilitate drug discovery, genomic research, chemical analysis and synthesis Chemical and biological weapons detection and analysis Huge device cost reductions Possible proliferation of controlled processing capabilities (e.g., nuclear isotope separation)	**Continued explosion** Photonics: bandwidth, computation Universal connectivity Ubiquitous computing Pervasive sensors Global information utilities Nanoscale semiconductors: smaller, faster, cheaper Natural language translation and interfaces **Effects** e-commerce dominance Creative destruction in industry Continued globalization Reduced privacy Global spread of Western culture New digital divides	**Extensive genome manipulation** GM plants and animals for food and drug production, organs, organic compounds Gene therapy **Effects** Longer life span Improved life quality and health Improved crop yields and drought tolerance Reduced pesticides and deforestation for farming Possible ecosystem changes Possibility of eugenics
Key enablers	Investments and commitment	Investments and development	Investments	Investments, S&T progress
Potential barriers	*Cost, manpower, acceptance*	*Technical issues*	*Backlash from globalization, creative destruction; world financial instabilities*	*Social and ethical rejection*
Low-growth futures	**Limited exploitation** Noninvasive diagnostics Improved drug delivery Functional building components Improved sensing and reconnaissance Integrated communication/entertainment **Effects** Incremental improvements in health care, energy efficiency, and environment	**Limited cross-modality integration** Mechanical sensors (e.g., gyroscopes) Assays on a chip **Effects** Emphasis on lateral development and technology spread rather than creation	**Slowed advancement** Slower yet continued technology development of current science breakthroughs **Effects** Parts of the world continue information technology drive; parts recede from information technology Continued e-commerce trends Possibly slower pace of technology acceptance and uptake	**Slow-go or no-go** Limited food, plant, and animal modification Reliance on traditional pest controls and GM procedures Continued use of traditional GM procedures (cross-pollination, selective breeding, and irradiation) **Effects** Increasing food and nutritional shortages in developing world Reliance on traditional pest controls and chemicals

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